# Adaptive Urban Dispersion Modeling (AUDIM)



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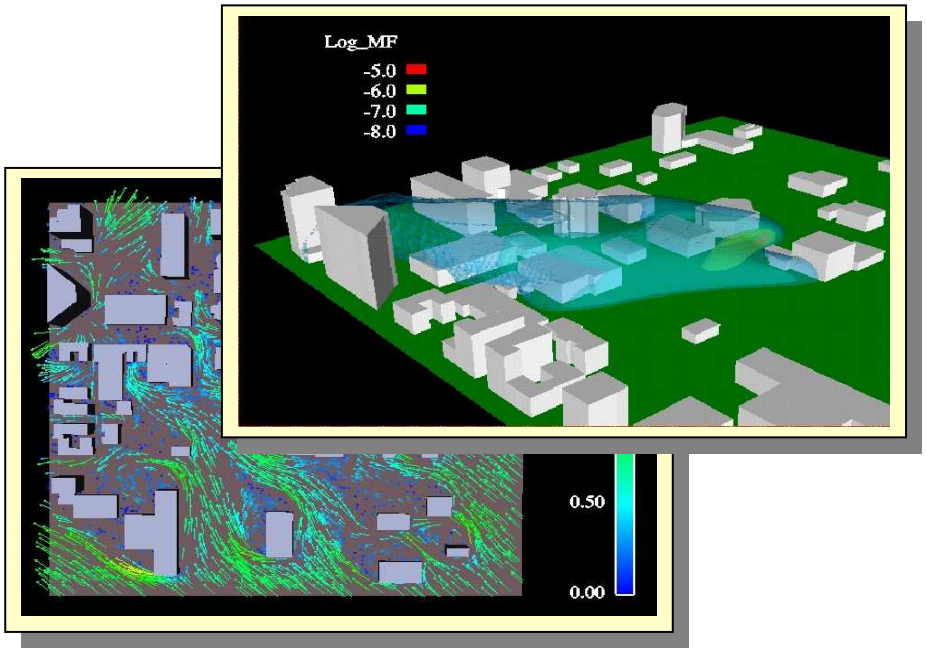
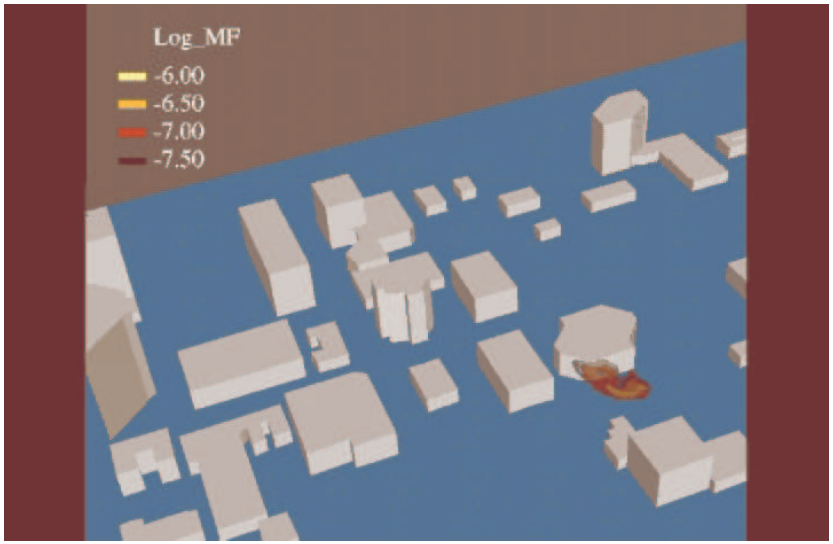
# Prediction of aerosol dispersion is a critical homeland security need

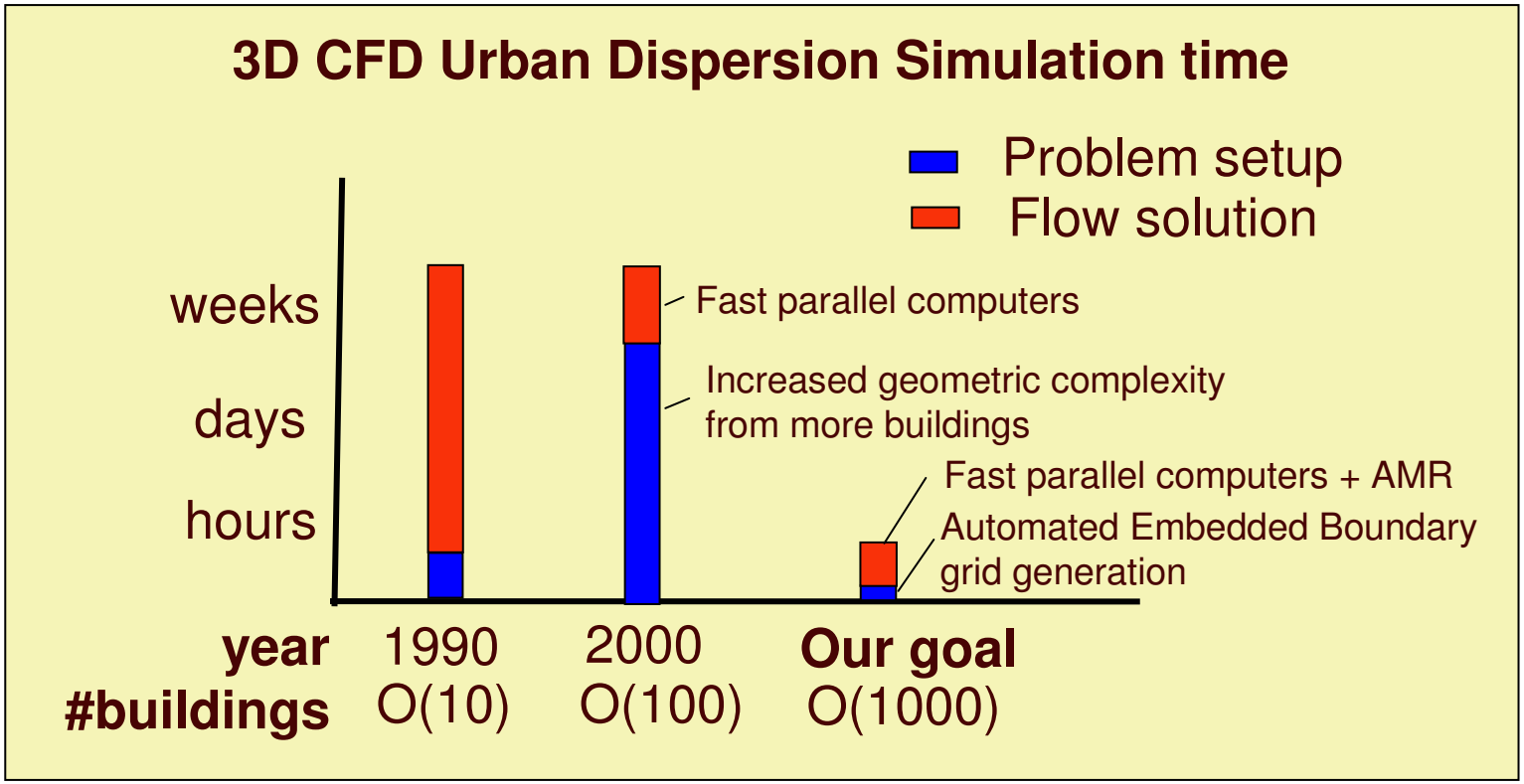
- **High fidelity models that predict the spread of airborne hazardous materials are important**
  - **Assist in emergency planning and response scenarios**
  - **Guide effective sensor placement**
  - **Event reconstruction (with measurements)**



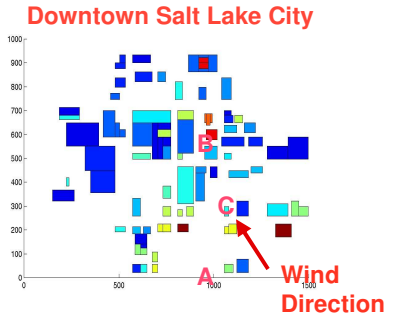
# Objective

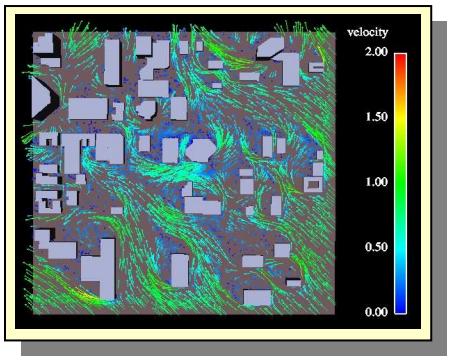
- **Develop an operational CFD capability to predict aerosol dispersion of hazardous materials in an urban environment.**

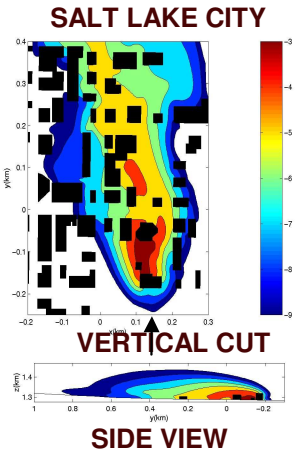


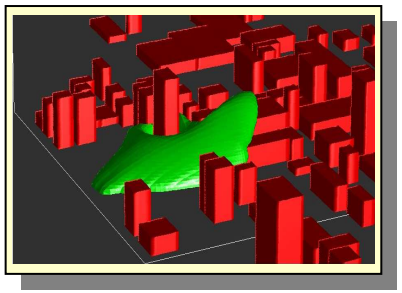
# FEM3MP CFD Model

- **FEM3MP is the primary urban dispersion modeling code used in the atmospheric sciences division in NARAC**
- **Validated from experiments**
  - **Joint urban 2003 in Oklahoma City**
  - **Urban 2000 in Salt Lake City**
  - **Windtunnel experiments**

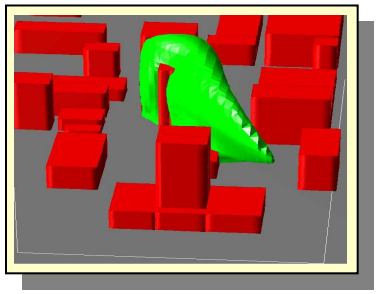


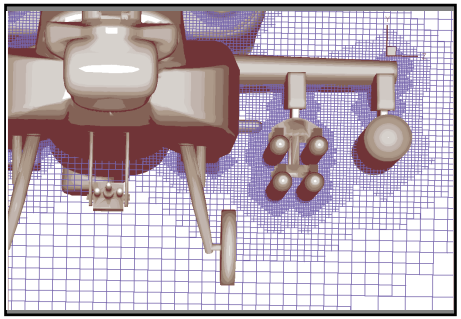
Release south of downtown (A)



Release in downtown area (B)

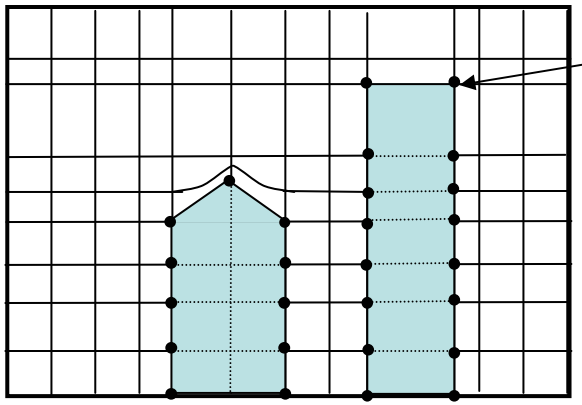
# Utilize Complex Geometry Embedded Boundary Cartesian Methods for Buildings

- **Constructing body-fitted logically rectangular grids is tedious and expensive.**
- **Embedded boundary grids constructed automatically in SAMRAI**
  - **Built from polygons or from surface triangulation using CUBES**
  - **Refinement enhances accuracy of boundary representation**

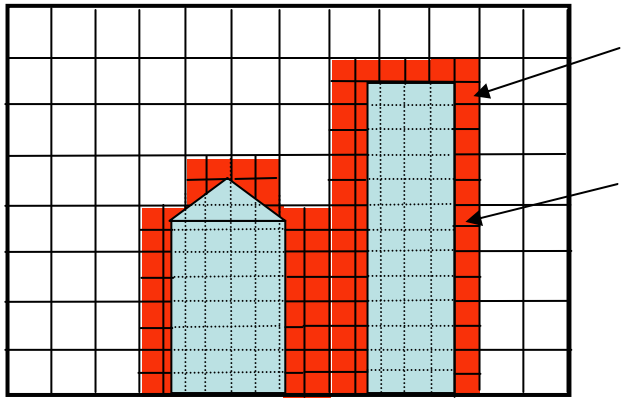


Example embedded boundary mesh constructed with CUBES

M. Berger, Courant Inst./NASA Ames



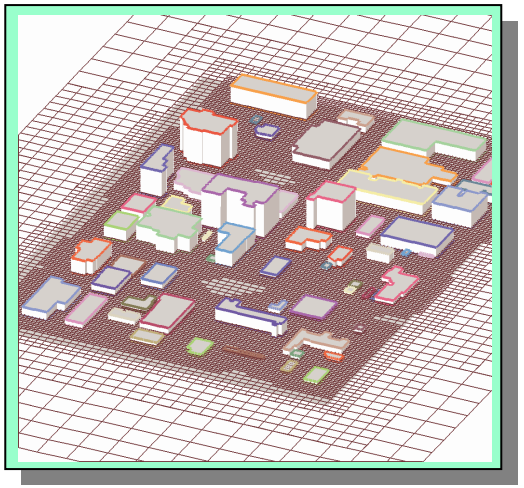

Body-fitted grid



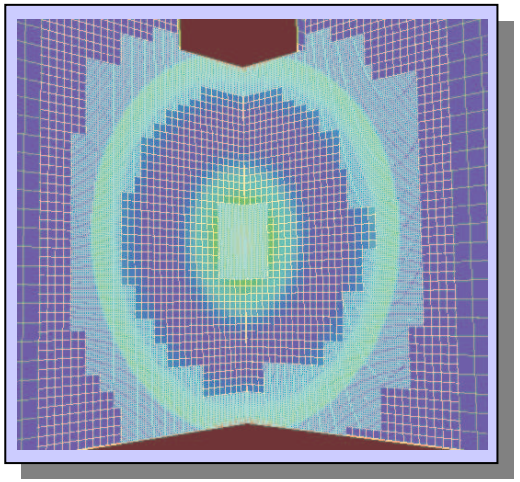

Embedded Boundary Grid

# Utilize advanced meshing tools developed at LLNL

- **Overture project has tools for rapid geometry-to-mesh (Rapsodi)**
  - Rapid construction of surface grids from CAD data
  - Developed to handle complex geometries



- **SAMRAI library supports parallel AMR applications**
  - Adaptive mesh refinement (AMR) automatically enhances simulation resolution where needed.
  - Runs on large parallel computer systems



# Couple advanced technologies to develop enhanced operational tool

**FEM3MP**
**CFD code for urban dispersion**

**SAMRAI**
**Parallel adaptive mesh support**

**Overture**
**Rapid geometry to mesh capability**

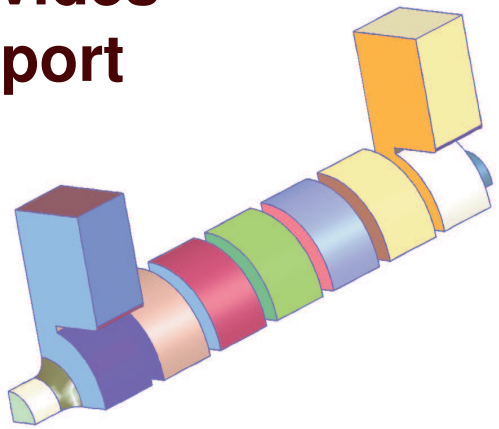
**Next-generation Integrated Urban Dispersion Capability**

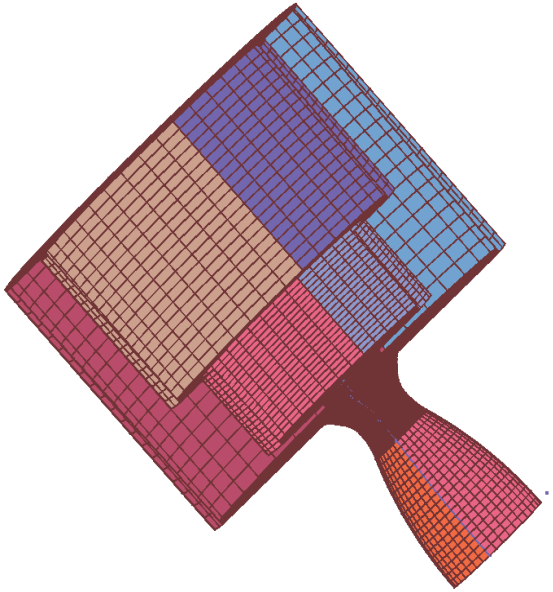
- **Automatic mesh construction from building datasets.**
- **Geometrically complex buildings and cityscapes**
- **Diverse urban environments:** stadiums, arenas, subways, etc.

- **Adaptive mesh refinement for enhanced fidelity:** release points, building entrances, etc.
- **Complex release scenarios:** moving sources, etc.

# Rapsodi/Eleven : geometry tools for efficient support of EB grid generation

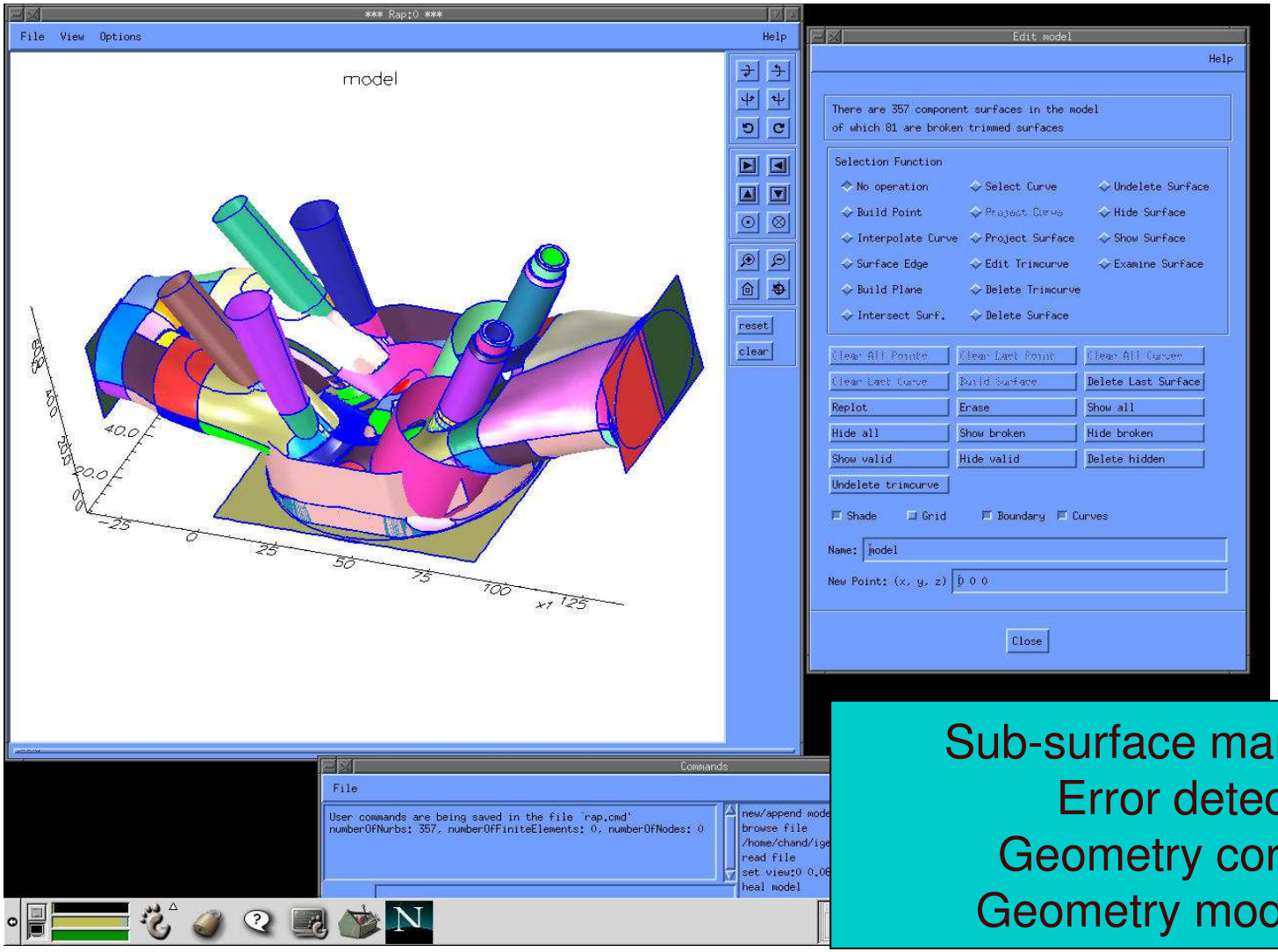
- **Rapsodi : Overture subset that provides Computer Aided Design (CAD) support**
  - IGES reader for complex CAD geometries
  - Extensive CAD fixup and editing utilities





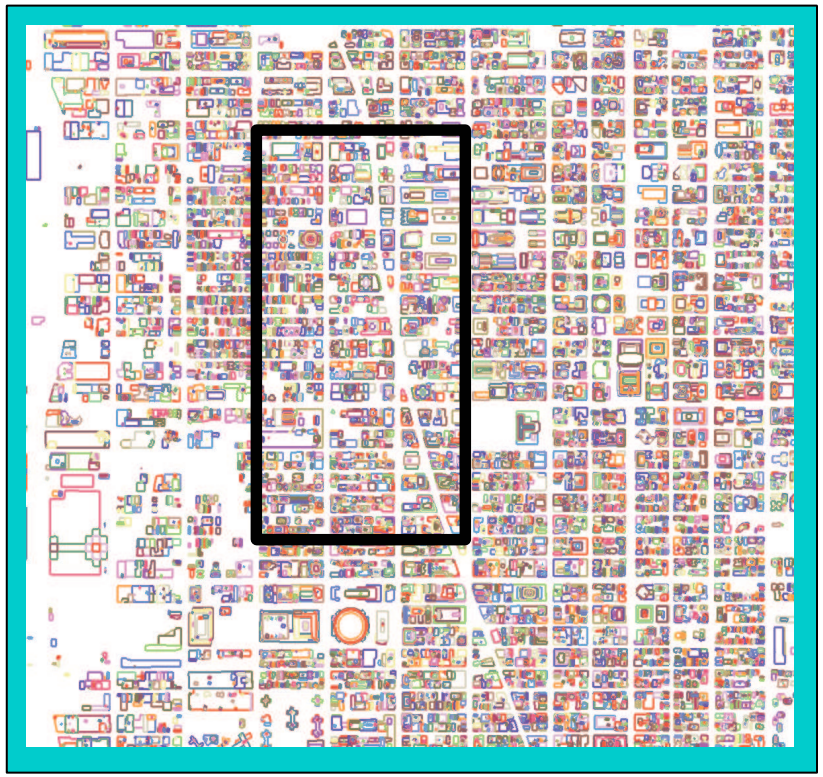
  - **Eleven : a small, independent library for EB grid generation**
    - Geometry representation, query and modification
    - Query API that takes advantage of block-structured AMR data structures
    - Can be called from inside a solver (e.g. SAMRAI) to evaluate geometry when generating refinement patches

# Rapsodi : CAD geometry editing tools




Sub-surface manipulation
Error detection
Geometry correction
Geometry modification

# Metro/Eleven : Interactive tools for modifying geometry

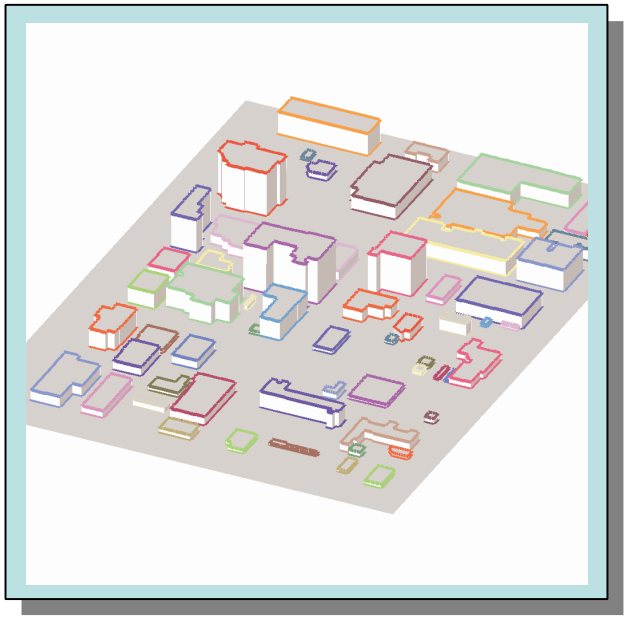


Modify/Add/Delete buildings
Clip out regions of interest
XML geometry database
Perl-scriptable text interface

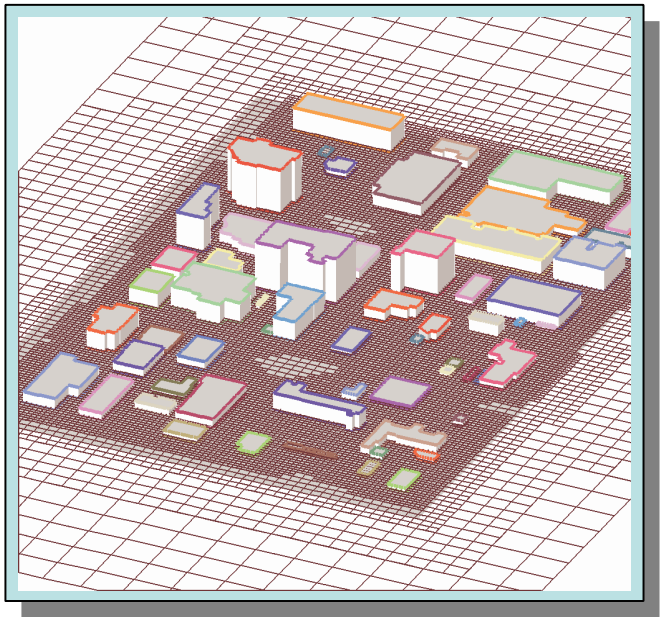
Metro is built upon the ELEVEN geometry library

# Automatic construction of grids from building datasets

- **Tool developed to read polygonal geometry data from NARAC and generate Cartesian adaptive grids.**



**Polygonal geometry data (Salt Lake City)**

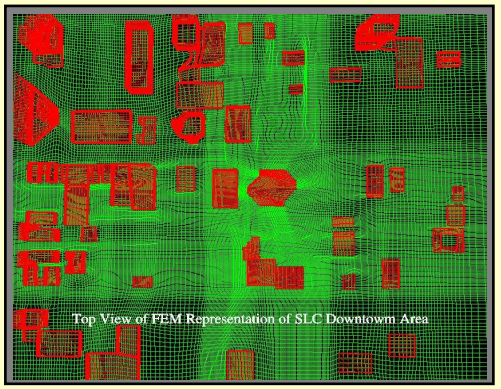


**Adaptive volume mesh by metro/CUBES**

# Grid generation time reduced from weeks to minutes

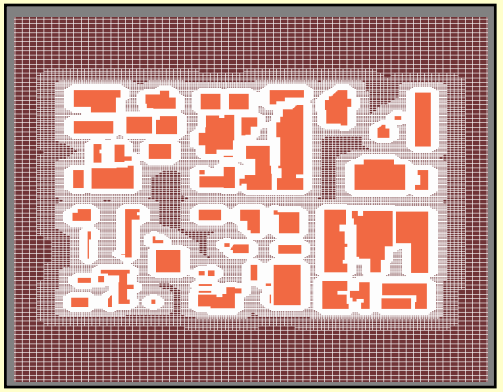
## Downtown Salt Lake City gridding example

- **Structured grid constructed with existing tools required about 1 week**

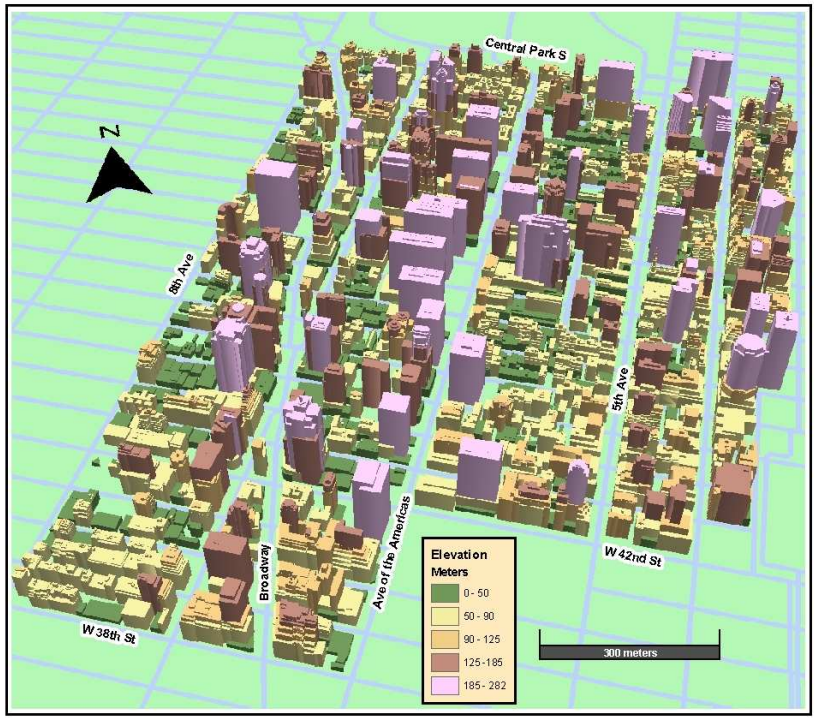



- **Adaptive cut-cell grid generated with metro/CUBES required about 2 minutes**

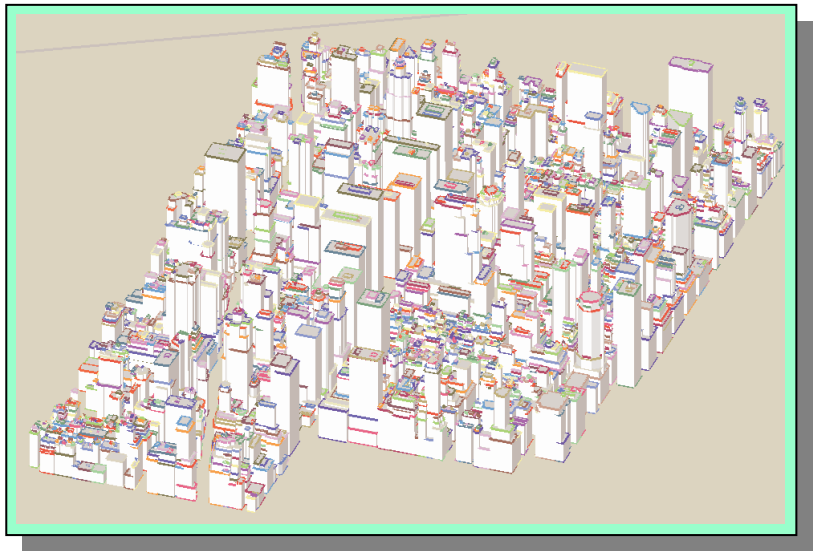
1.7M gridpoints, 6 levels refinement
Surface grid – 30 sec with "metro"
Volume grid – 45 sec with "CUBES"

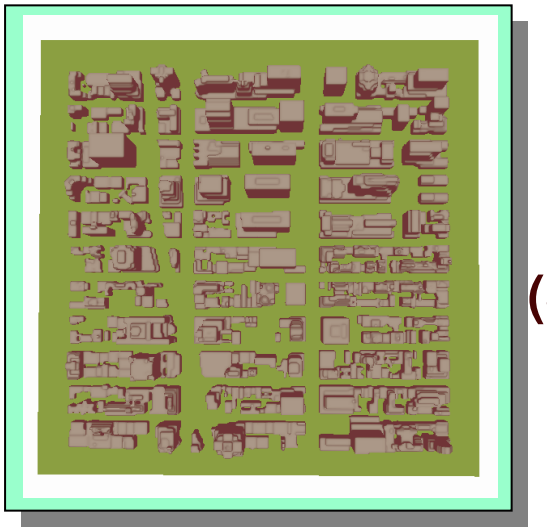


# Tools utilized to mesh complex cityscapes




**Midtown Manhattan**

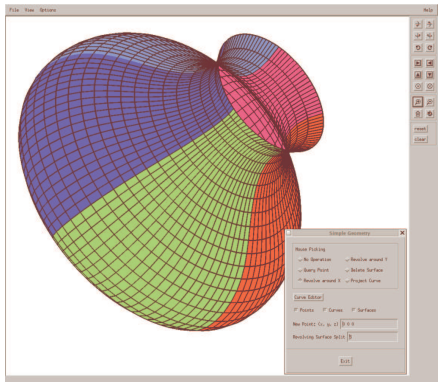




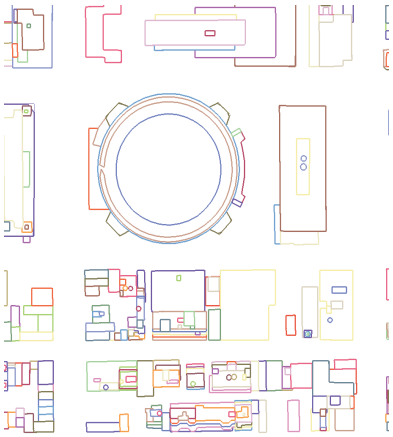
**Polygonal geometry representation by metro (3600+ polygons)**

Times Square

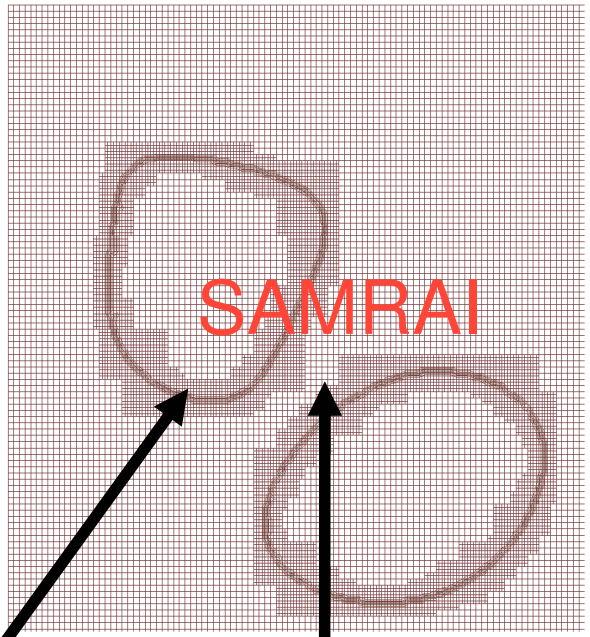
# Agile geometry tools for EB applications

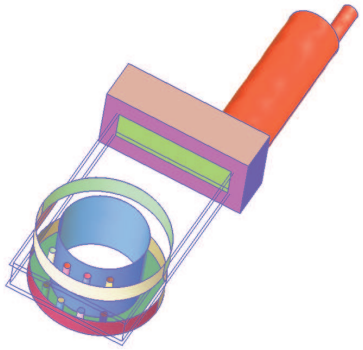


Manual input



GIS Shapefile/DEM



CAD (Rapsodi)

ELEVEN

CUBES

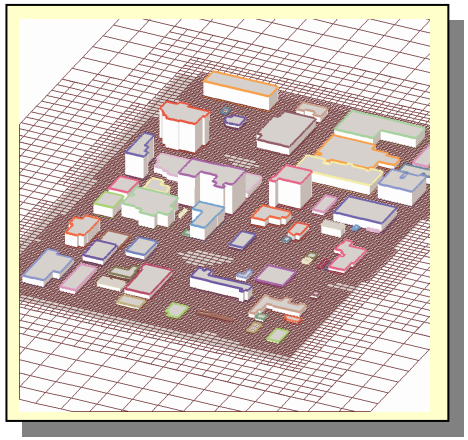
Other sources...?

# Integrated approach will enable automated geometry to CFD analysis

LIDAR Image of World Trade Center Debris Field

**Overture (Rapsodi)**
Surface grid generation

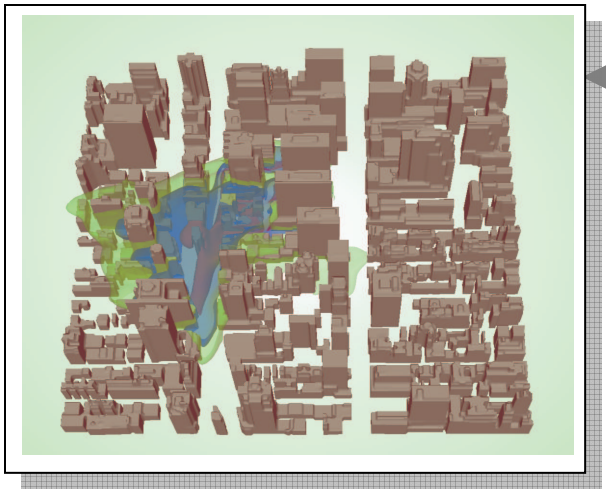
**CUBES/SAMRAI**
Volume Grid generation



Adaptive Cartesian grid

**FEM3MP**
CFD & Dispersion Models

**SAMRAI**
Adaptive meshing, complex geom defn

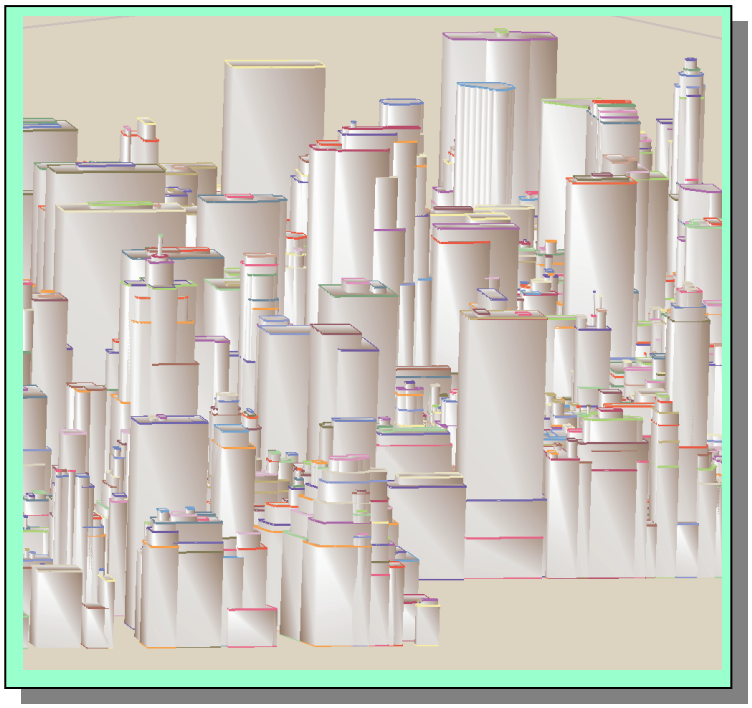


Parallel Adaptive flow solution

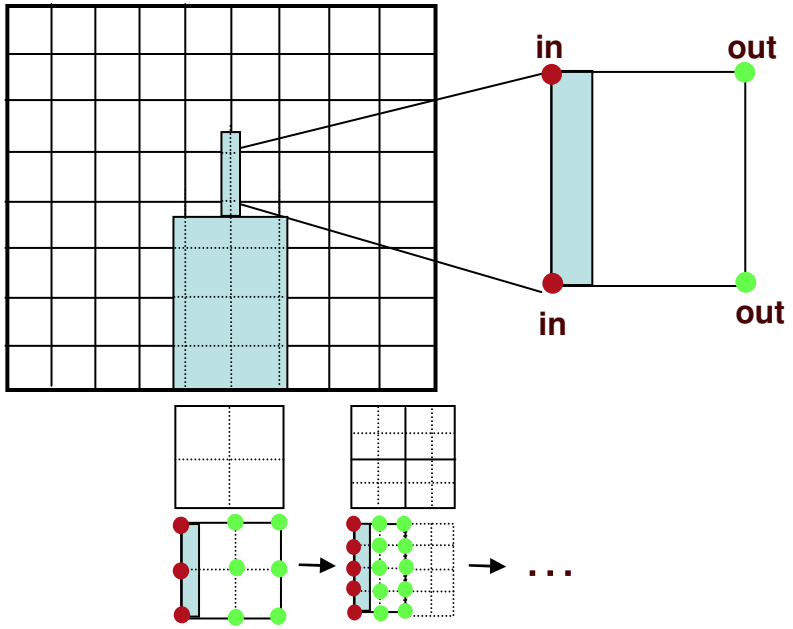
Links exist

Developing links

# SAMRAI/Eleven links enable modeling of complex cityscapes



- **Generating triangulated surface difficult or impossible**
- **Inside/outside determination using Polygons**




**Eleven**
Inside/outside determination

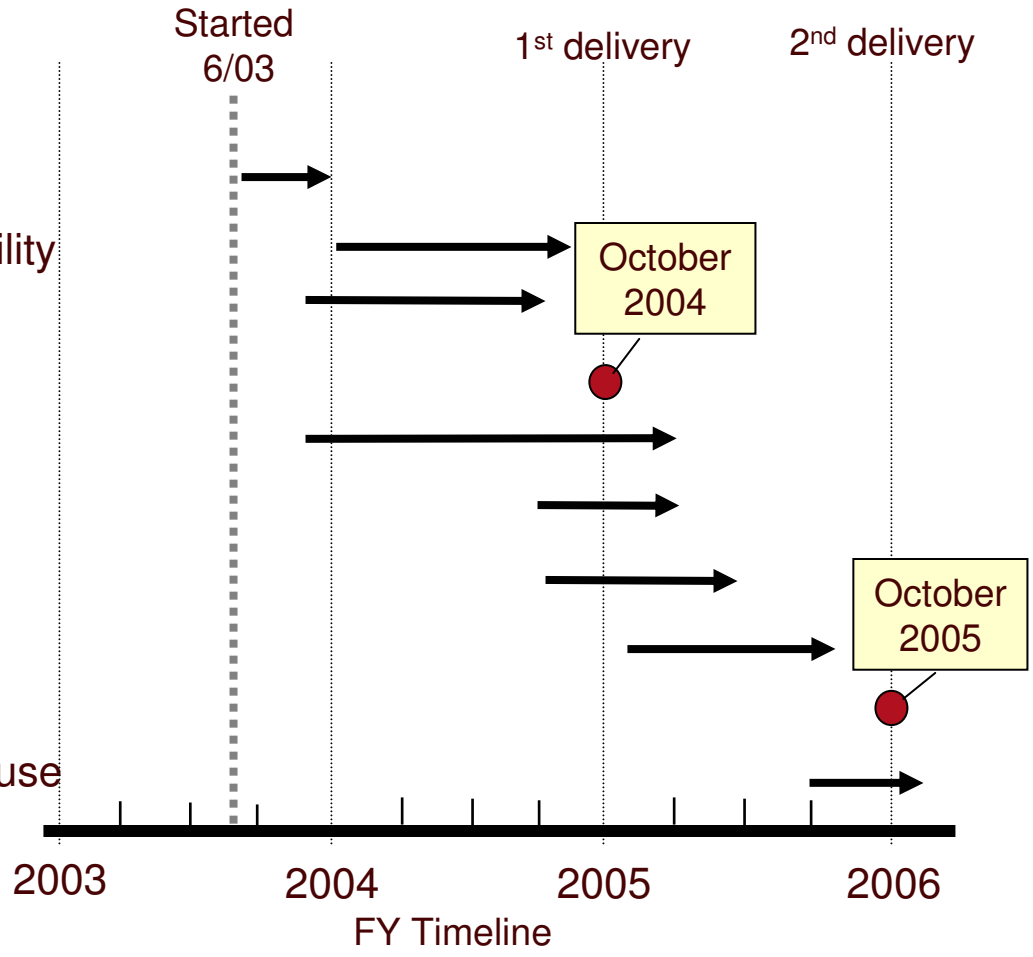
→ ←

**SAMRAI**
Mesh construction

Enhanced accuracy through refinement

# Project tasks and timeline

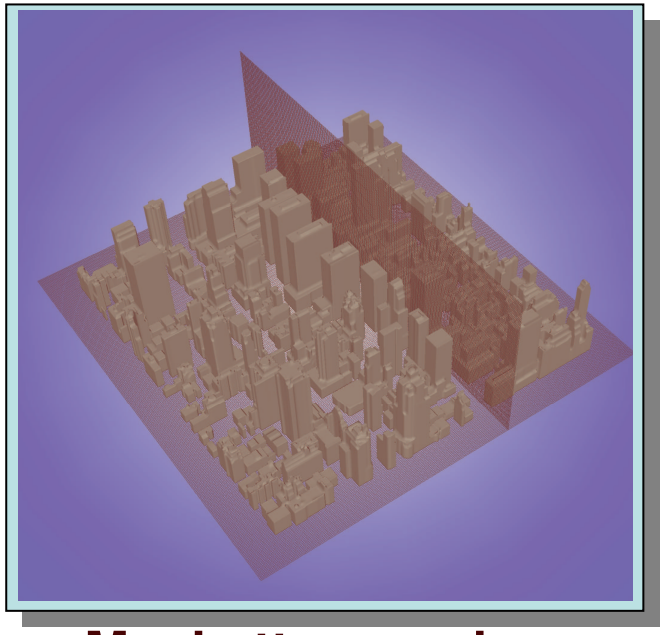
- Demonstration calc with prototypes
- Demonstrate geometry-to-mesh capability
- Develop complex geometry in SAMRAI
- **Deliver gridding tools for NYC**
- SAMRAI-FEM3MP integration
- Develop cut cell FE algs
- Develop AMR capability
- **Deliver adaptive flow solver**
- Fine-tune performance for operational use



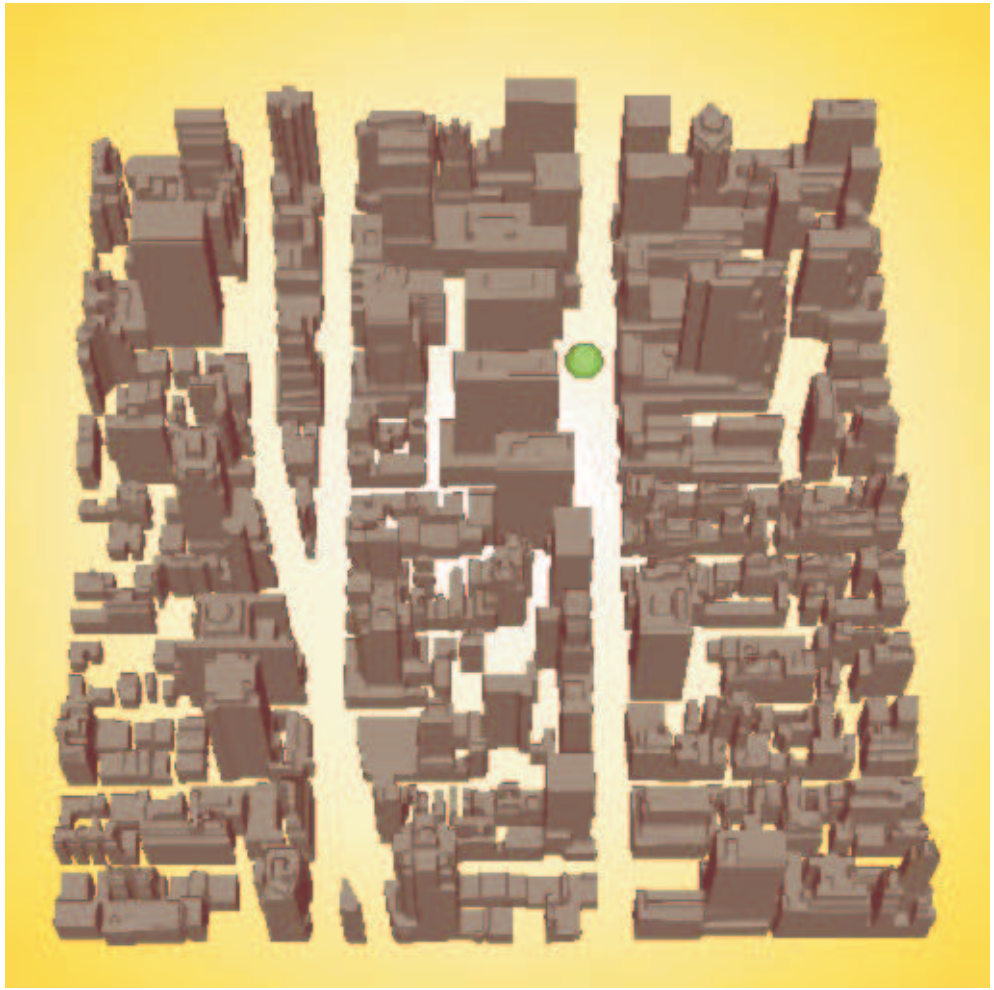
# First set of delivered tools are being used for Manhattan studies

## Manhattan simulations

- DHS-funded Urban Dispersion Project (UDP)
- Meshing tools used for CFD simulations

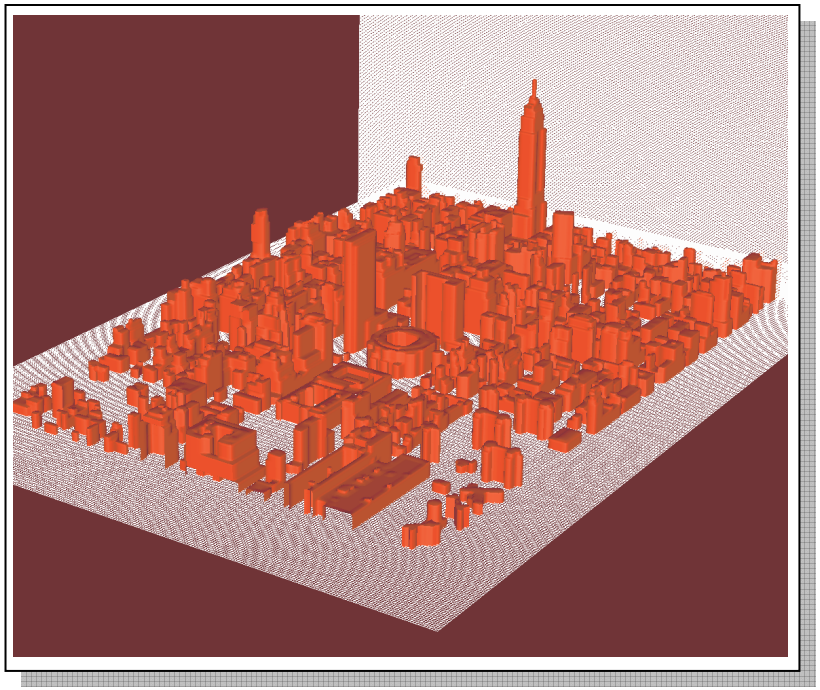


Manhattan meshes
Rapsodi/SAMRAI

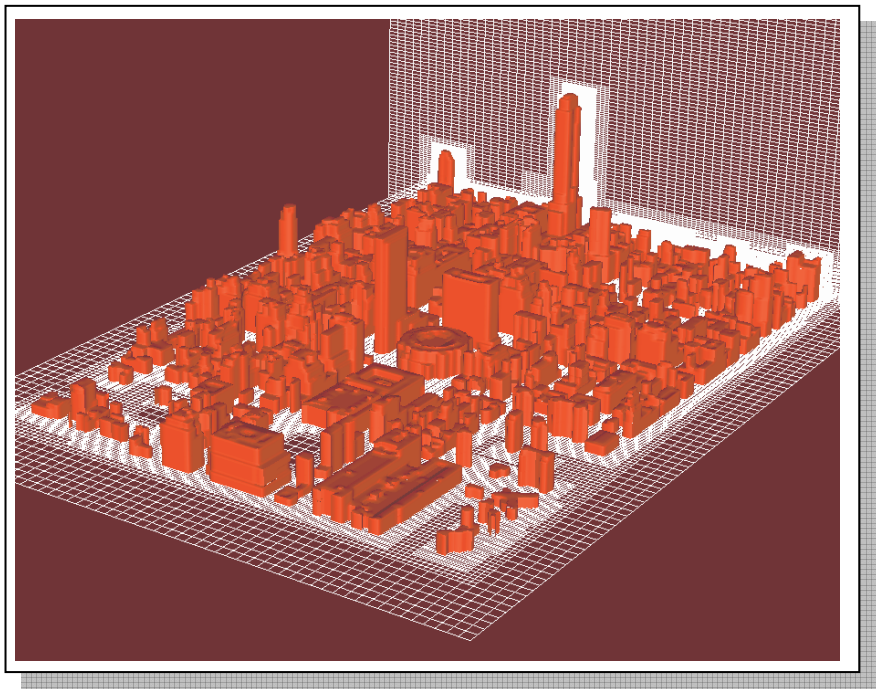


CFD Calculation (non-adaptive)
FEM3MP

# Grid adaptivity will significantly reduce flow solution time



Uniform grid (non-adaptive)
**33.6 M** gridcells



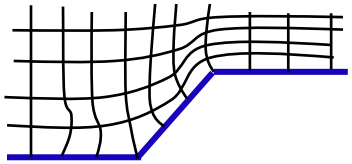
AMR grid
**3.4 M** gridcells

**Lower Manhattan – Madison Sq. Garden/Empire State building**

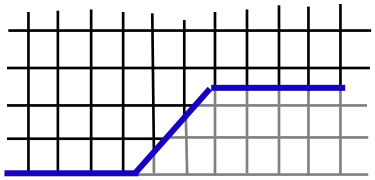
Resolution: 5m horizontal, 2m vertical

# Algorithmic research issues being addressed in this work

- **Finite element boundary representation on cut-cell grids using "fictitious domain" algorithm**



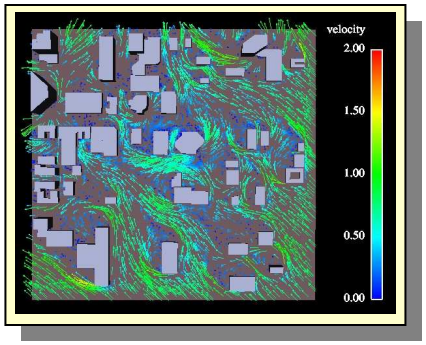
"conforming" mesh



"cut-cell" mesh

- **Adaptive algorithms for finite element CFD solver**
- **Turbulence models**

RANS

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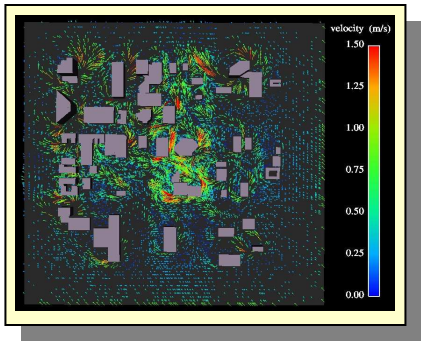
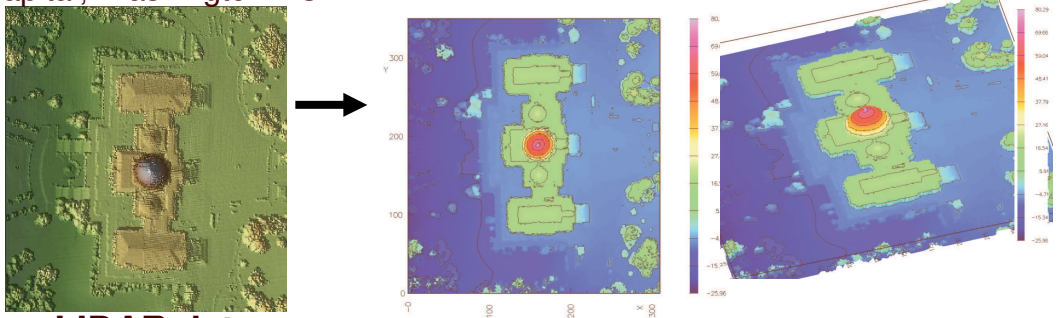



- **Building geometry information that incorporates new features (e.g. terrain)**

# Future: Coupling image processing technologies to simulation

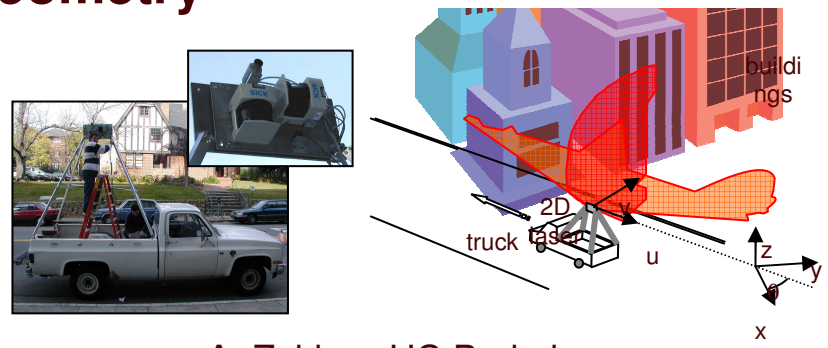
- **Automated airborne LIDAR-to-grid capability**
  - Currently use building shapefile input – limited number of cities available
  - LIDAR data available for almost any US city

Capital, Washington DC



**LIDAR data** **Surface Grid for simulation**

- **Higher resolution building geometry**
  - Better resolution of building facades
  - Extensions to large indoor spaces

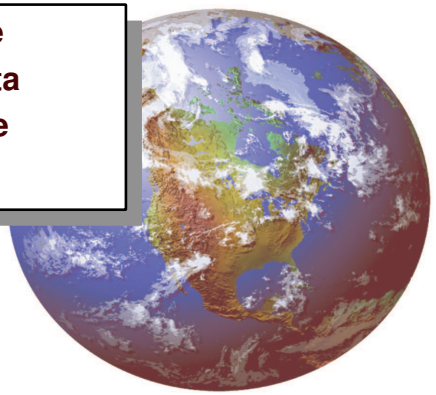



A. Zakhor, UC Berkeley

# AUDIM will be a part of NARAC operational capability

**World-wide data coverage**

- Real-time weather data
- Terrain & land surface
- Maps



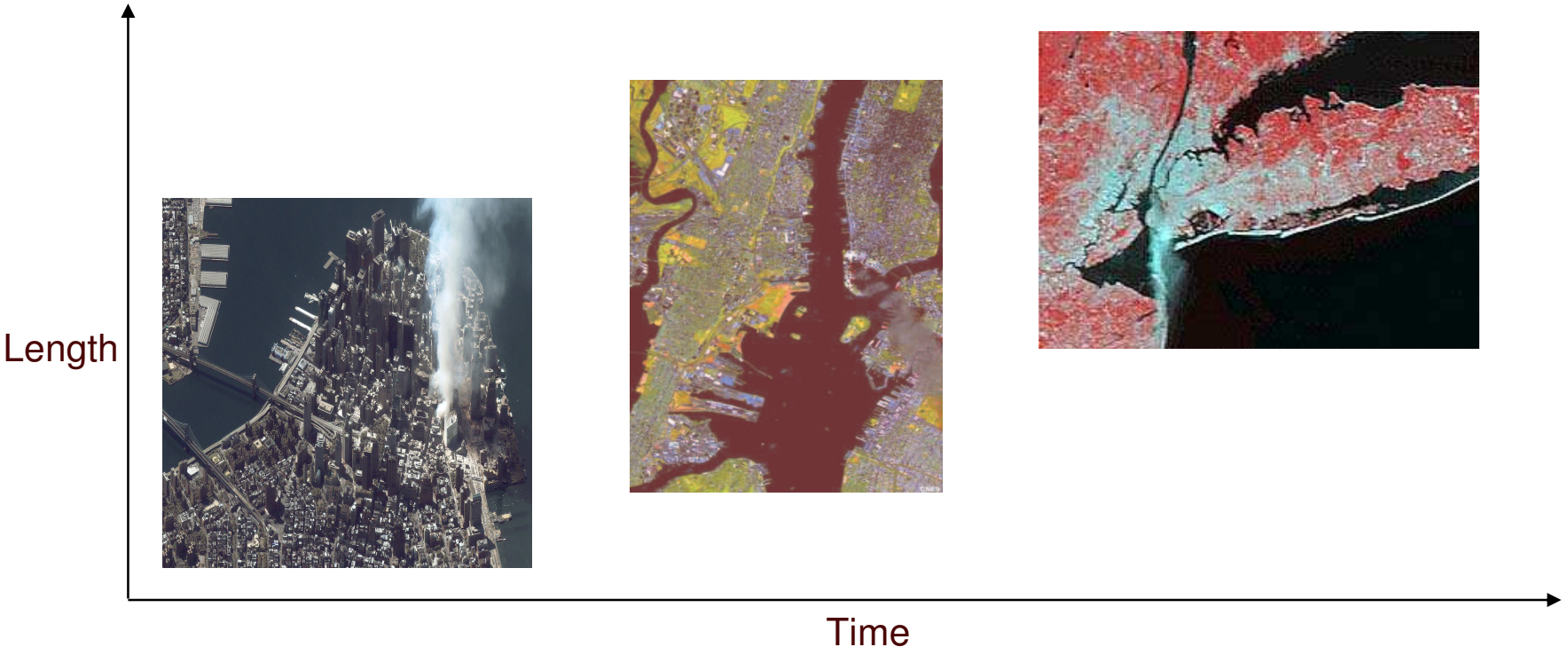
**National Center at LLNL**

- Advanced, automated 3-D modeling system
- Scientific and technical staff provides quality assurance and assistance 24 hrs x 7 days


**Real-time Hazard Advisories**

- Nuclear, radiological, chemical, biological & natural releases
- National center predictions available within minutes using Internet/Web tools
- Deployed modeling tools on end user's computer
- Geographical information displays
- Affected population, health risks, recommended actions

# Need: Efficient, flexible, and accurate operational urban dispersion capability




- **Current CFD urban dispersion models are research and planning rather than operational tools**
- **Operational urban plume dispersion tool must be fast, flexible and accurate**

# Priorities for improving dispersion modeling addressed in recent NRC report

**NRC of the National Academies report** "Tracking and Predicting the Atmospheric Dispersion of Hazardous Material Releases – Implications for Homeland Security"

"New dispersion modeling constructs need to be further explored and possibly adapted for operational use in urban setting. This includes advanced short execution models, slower but more **accurate computational fluid dynamics** and **large-eddy simulation** models and models with adaptive grids." (page 5.)

"**…** no one system had all the features that the committee deemed critical:

- accommodation of **urban and complex topography**
- accurate though slower models for the **preparedness and recovery** phase"

# Event Reconstruction Answers the Critical Questions: What? When? Where? How Much?

**What?**
**When?**
**Where?**
**How much?**

*Release Event*

*Observations (visual, sensor, casualty)*

*Unknown Source*

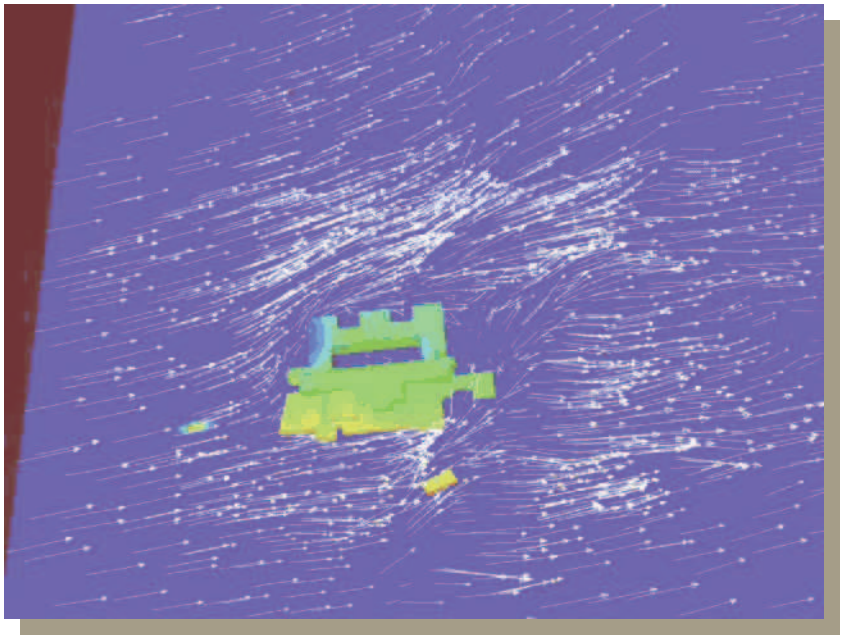
*Consequence Management*

- **Atmospheric releases are one of the most highly effective and rapid means to impact large populations**
- **Primary uncertainty due to unknown sources and meteorology**
- **Our approach couples data and predictive models to provide**
  - **Backwards analyses to determine unknown source characteristics**
  - **Optimal forward predictions for consequence assessment**
  - **Dynamic reduction in uncertainty as additional data become available**

# Urban Dispersion Modeling using FEM3MP

**Our current capability:**

- FEM3MP – a stand-alone CFD code
  - finite element code (terrain/shape following coordinates)
  - parallelized using MPI
  - solves steady state and time dependent problems

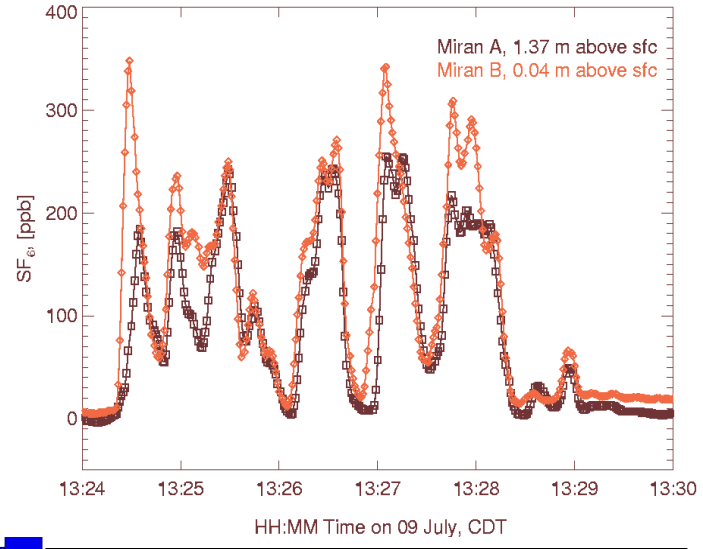


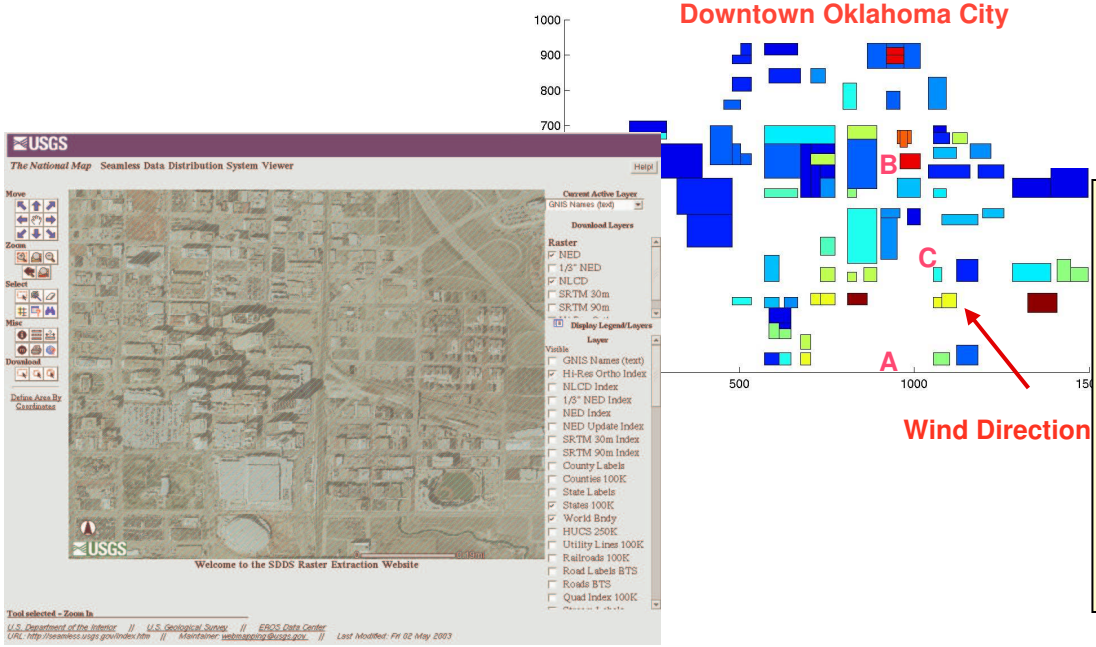
**Current Limitations:**

- **Limited capability for simulation of fast evolving flows**
- **Treatment of inflow, outflow and lateral boundary conditions**
- **Range of release scenarios**
- **Simpler geometries**
- **Labor-intensive grid generation capability**

# We use experimental measurements to verify and validate urban dispersion code

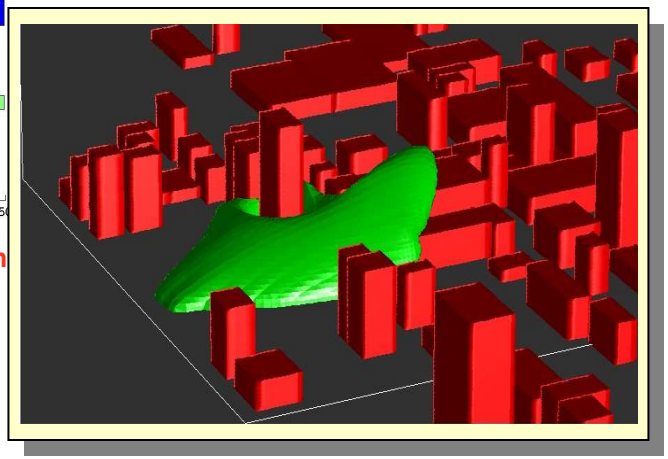
- **Joint-Urban 2003 in Oklahoma City (took place in July 2003)**
- **Urban 2000 in Salt Lake City**
- **Wind tunnel experiments**





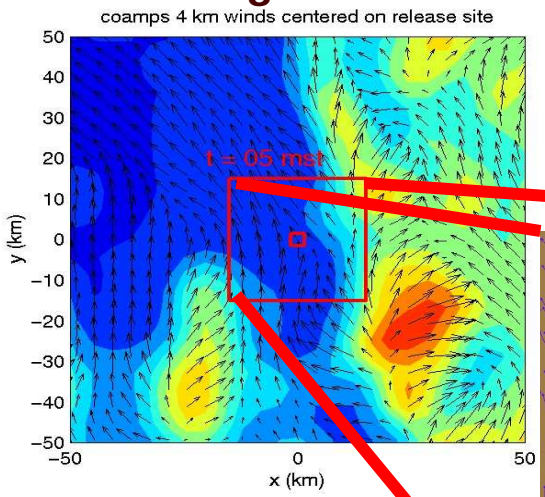




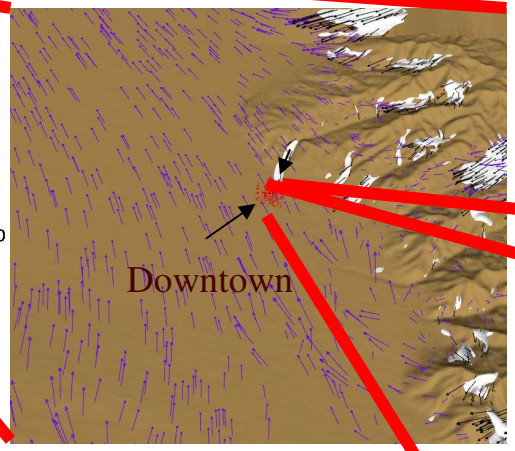
# Seamless coupling between regional and urban scale models will be possible

Urban scale models resolve small scale flows which must be parameterized in large scale models – considerable current scientific interest

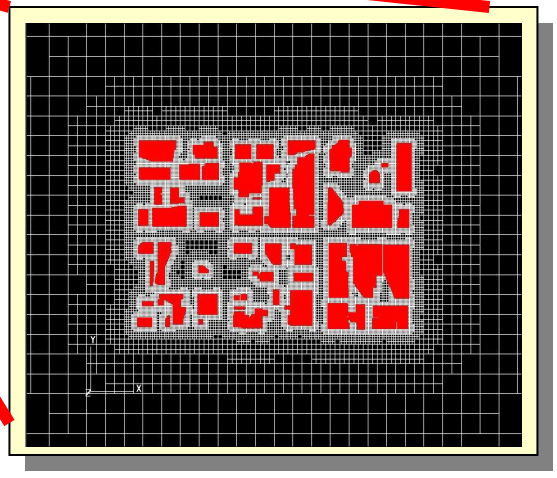
**REGIONAL SCALE**
**4km grid size**




**MESOSCALE**

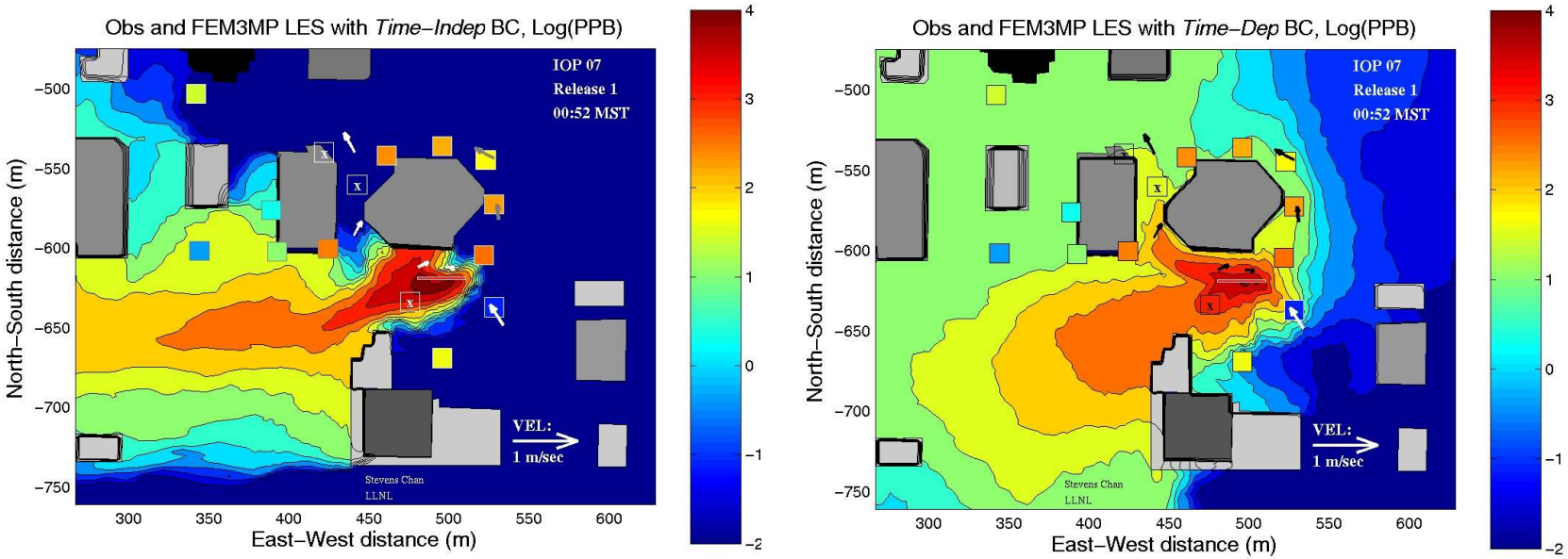



**URBAN SCALE**
**1m grid size**



**Coupling will provide accurate boundary conditions for urban scale simulations**

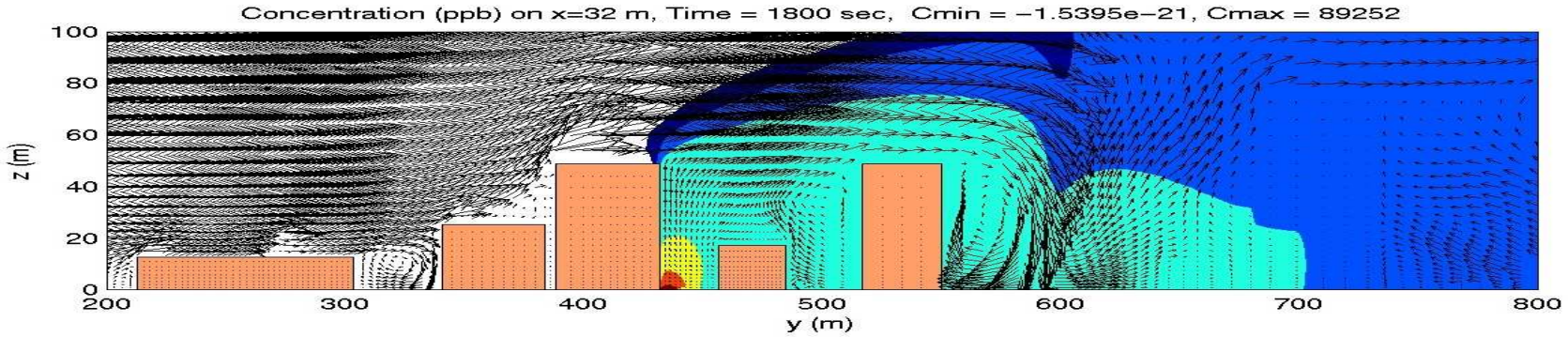
# Accurate time dependent forcing is essential for prediction of dispersion



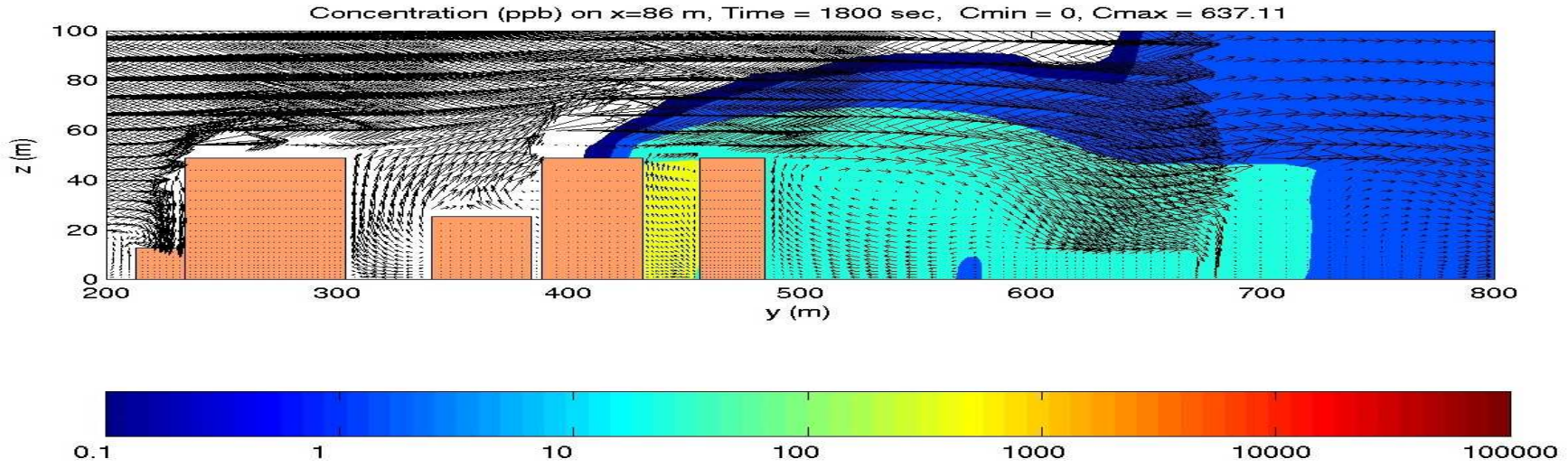

**More accurate urban dispersion prediction will be achieved through seamless coupling with a mesoscale model which will provide time dependent forcing for urban-scale flows**

# Predicted Wind Vectors and Concentrations in Downtown OKC

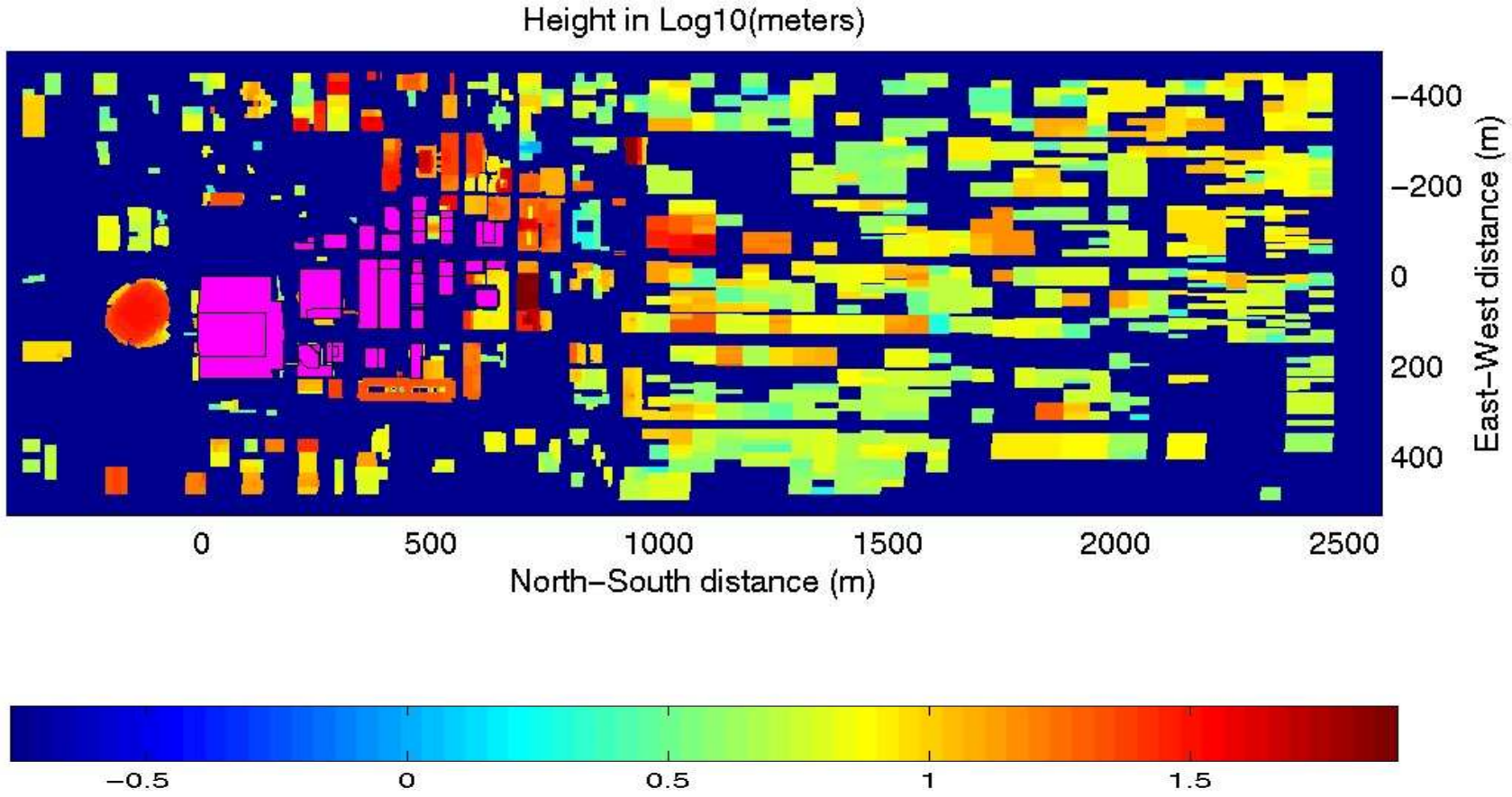
## (a) Through Release Point




## (b) Through Sonic Building

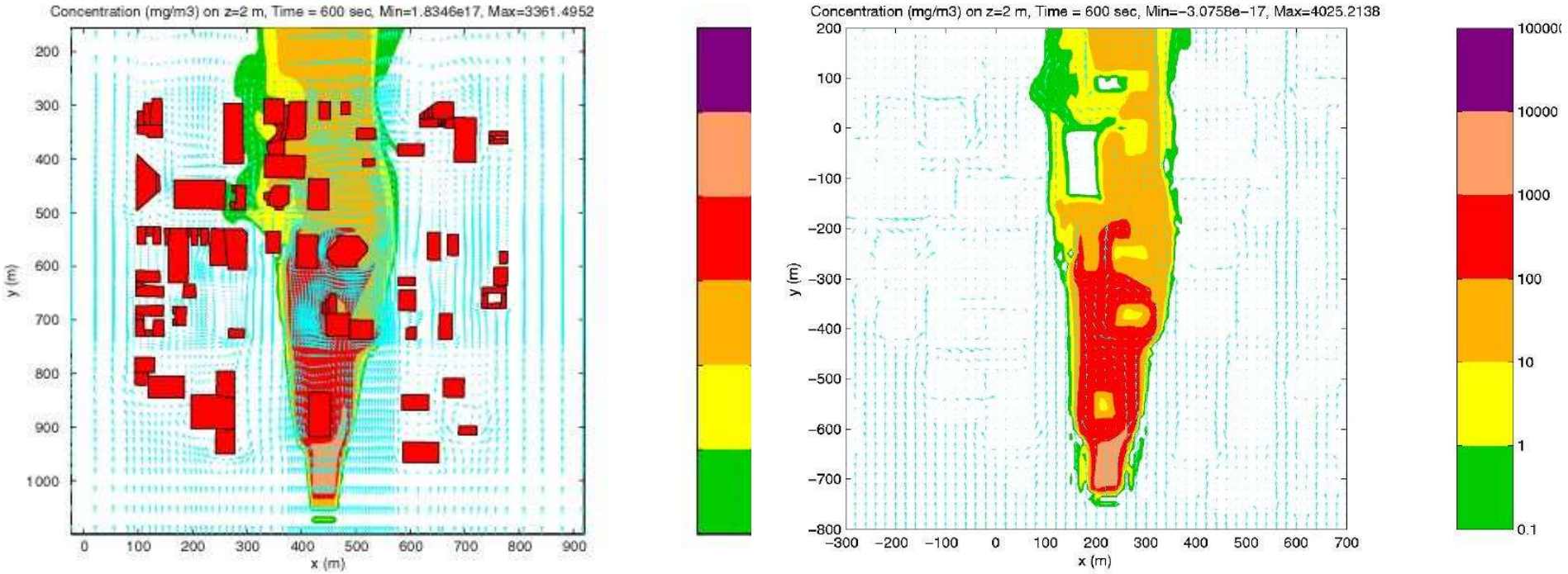


# Oklahoma City Downtown Modeled with Explicitly Resolved and Virtual Buildings



# We use virtual building technique for efficient representation of buildings

Comparison between surface dispersion patterns 2m above surface for a hypothetical release



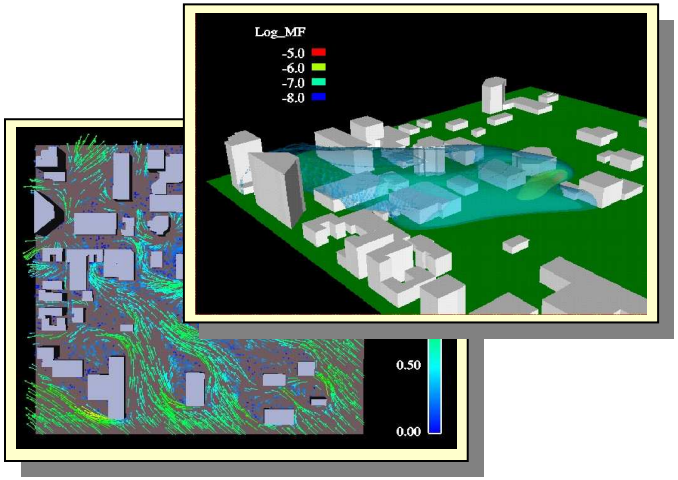

**Fully-resolved results**

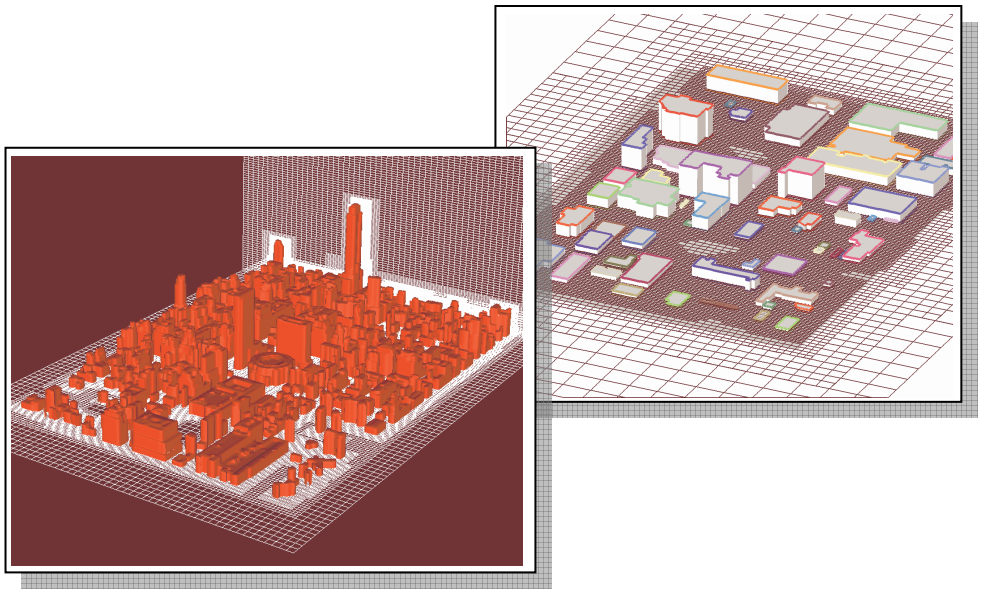
**Virtual representation**

**10m uniform grid resolution**

# Conclusions

- We are developing new capabilities by combining expertise and tools from two groups at LLNL – COMP and NARAC
- Automatic geometry-to-mesh and adaptive gridding tools will significantly enhance NARAC's operational urban capability
- Tools developed are already being used (for studies in Manhattan) and have the potential to become the standard urban simulation capability in NARAC.



# Acknowledgments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- Document UCRL-PRES-208459